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HYDROSTATIC TRANSMISSION CONTROL FOR OFFSHORE WIND TURBINES

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Abstract. This paper aims to investigate the dynamic closed-loop co-simulation of overall offshore wind turbine systems with hydrostatic transmission control. This methodology consists of aerodynamics, mechanism dynamics, control system dynamics, and subsystem dynamics. Aerodynamic and turbine properties were modelled in FAST; ADAMS performed the mechanism dynamics; control system dynamics and subsystem dynamics such as generator, pitch control system and yaw control system were modeled and built in MATLAB/SIMULINK. Thus, this comprehensive integration of methodology expanded both the flexibility and controllability of wind turbine. The simulation of closed-loop control of overall offshore wind turbine with hydrostatic transmission system will be analyzed and investigated. The hydrostatic transmission is installed between the rotor and generator. The hydrostatic transmission consists of a fixed displacement pump and a variable displacement motor where the pump is mounted on the shaft in the low speed shaft (LSS) and the motor is mounted on the high speed shaft (HSS) which connects to the generator. Finally, the dynamic performance and responses can be observed in this study.

Keywords: offshore wind turbine, hydrostatic transmission control, aerodynamic, pitch control.

INTRODUCTION

The power of the wind has been discovered for over 3000 years, which the original idea is used for generating mechanical power to grind the grain. Then the wind power technology moved to a new level after 20 centuries. About 5% annual increase in the energy field of the wind turbine can be attributed from the advances in aerodynamics, structural dynamics, and the skill of produce. After 1980s, people focused on extracting more electrical power from the wind instead of mechanical power and the size of wind turbine has extended gradually from less than 100kW in early 1980s up to 8MW nowadays. The mega-watt sized wind turbines usually connect with two types of generators: permanent magnetic synchronized generator and double-fed inductive generator. The former generator was derived with the rotor directly and the latter also connected with a gear box to speed up. However, the wind speed is fluctuated and random in virtual conditions. That would affect the generator-side speed in both types of generators. Furthermore, the small vibrations would wear the components and excite the oscillation to damage the machine. To improve this defect, the researcher figured out a novel method by using hydraulic technologies which has been well developed in car speed changing system, while it seldom applied to large-size turbine systems.

Appropriate control is one of research areas where such improvement can have a great influence on a wind turbine[1]. There are two perspectives for control target, either better electrical power production efficiency, or optimal mechanical performance to get benefits from energy source. The former focus more on power extraction and the energy loss from the grid side, several studies on generator and grid control have been developed. In 2007, Guo developed a direct power control system for a 2MW wind turbine driven by doubly-fed induction generator[2]. With the advantages of energy capturing, active and reactive power regulation[3], and lower power losses, DFIG has become one of the most popular solutions for wind energy utilization. Another renowned generator is known as permanent magnetic synchronized generator (PMSG), with the power control capability built by Deng, 2009[4]. The direct drive interface to the grid through converter offers a higher power density and controllability to the wind turbine. What's more, it also allows us to use smaller poles than conventional generators, so these machines can be designed to rotate at rated speeds for a large mega-watt turbine.

Another major issue of wind turbine designs is that both PMSG and DFIG should connect to the frequency converters so that power can be linked to the grid. The generator speed will be varying due to the rotor speed from low speed shaft even when mechanical gear box sets are installed. A fixed or discrete variable gear ratio limited the speed in high speed shaft which makes a converter become necessary. Thus, a variable speed transmission becomes one of the solutions to solve the question. A continuously variable transmission (CVT) option, hydrostatic transmission (HST), is introduced [5-8]. This drivetrain can replace conventional gearbox in a wind turbine application not only because of its high power ratio but also its compact size when comparing with mechanical drivetrain. HST, combines good efficiency and grid stability with high reliability and low costs, utilizes a variable angle of swash plate design to vary speed in high speed shaft so that a step-like speed transition can be avoided during operation. Furthermore, HST also decouples the rotor speed from generator speed, allowing the generator run at synchronized speed regardless of upcoming wind.

Consequently, an idea of hydrostatic transmission integrated into a large wind turbine transmission is determined. To realize this objective, a mathematic model of hydrostatic transmission is derived and modeled in MATLAB to replace with conventional gearbox. Then the model of transmission works simultaneously with wind turbine simulation software FAST [9-10] and ADAMS [11] such that the state variable of the wind turbine can be feedbacked to the transmission model. Meanwhile, other subsystems including pitch / yaw and doubly fed induction generator are developed in simulation as well.

The organization of this paper can be divided as follows: the mathematic model of hydrostatic transmission is derived in the next Section and the control law and strategy are presented in control law section. The dynamic responses of hydrostatic speed control wind turbine are illustrated in simulation and which are also compared with referenced direct-drive wind turbine.

MODELLING OF HYDROSTATIC TRANSMISSION SYSTEM

In this section, we aim at building up a mathematic model of hydrostatic transmission system for wind turbine. A schematic diagram of hydrostatic speed controlled wind turbine is shown as figure 1. The hydrostatic transmission is installed between the rotor and generator. The hydrostatic transmission consists of a fixed displacement pump and a variable displacement motor where the pump is mounted on the shaft in the low speed shaft (LSS) and the motor is mounted on the high speed shaft (HSS) which connects to the generator.

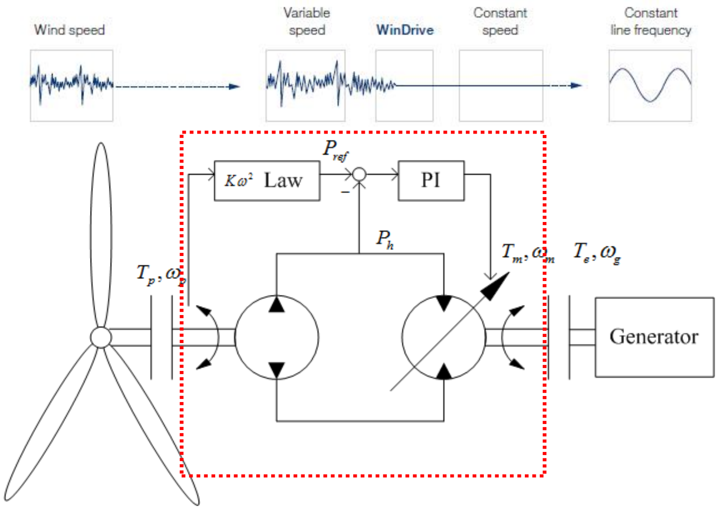

FIGURE 1. Schematic diagram of hydrostatic speed controlled wind turbine.

A fixed displacement hydraulic pump converts the turbine rotor rotational motion to fluid flow. By using the Newton's 2nd law, the first-order dynamic equation can be expressed as Eq.

$$\tau_r - \tau_p = J_p \dot{\omega}_r \tag{1}$$

We consider τ_r and τ_p are the resultant torque generated by pump and rotor respectively and ω_r is defined as rotor speed. The resistant torque can be derived as a function of pump pressure and displacement:

$$\tau_p = \frac{\Delta p \cdot D_p \cdot 2\pi}{\eta_{mech,p}} \tag{2}$$

the flow rate of the pump can be characterized as Eq.(3) with volume efficiency $\eta_{vol,p}$:

$$Q_p = \eta_{vol,p} \cdot D_p \cdot 2\pi \cdot \omega_r \tag{3}$$

After defining the dynamic model of the fixed pump, the motor dynamic can be formulated by using the first order dynamic equation. Most of generator comes with controllers which helps generator extract desired torque under specific speed. τ_m is the torque driven by fluid flow from motor sides so we can calculate the motor torque from the fluid power:

$$\tau_m = \frac{\eta_{mech,m} \cdot \Delta p \cdot D_m}{2\pi} \tag{4}$$

In order to achieve continuous variable speed control, a variable displacement motor is chosen to create the controllability. By changing the displacement, the speed will vary with the same volume flow input. Therefore, Eq.(5) expresses the relation of volume flow Q_m and D_m displacement:

$$\eta_{vol,m} \cdot Q_m = D_m \cdot 2\pi \cdot \omega_g \tag{5}$$

For most industrial products, variable displacement motor is integrated with an internal feedback controller to guarantee the linear proportion of commend current signal and displacement. As well as this assumption, the dynamics between commend signal i and displacement will be shown as Eq.(6):

$$D_m = \frac{i}{i_{max}} D_{m,\max} \tag{6}$$

Since the flow rate Q_m at motor side is directly sorted from the pump side Q_p, the volume flow difference between them makes pressure change. By applying continuous equation, the pressure from the high-pressure port is expressed as Eq.(7):

$$p_h = \int \frac{\sum Q}{C_H} dt \tag{7}$$

Consequently, the control block diagram of HST will be illustrated as

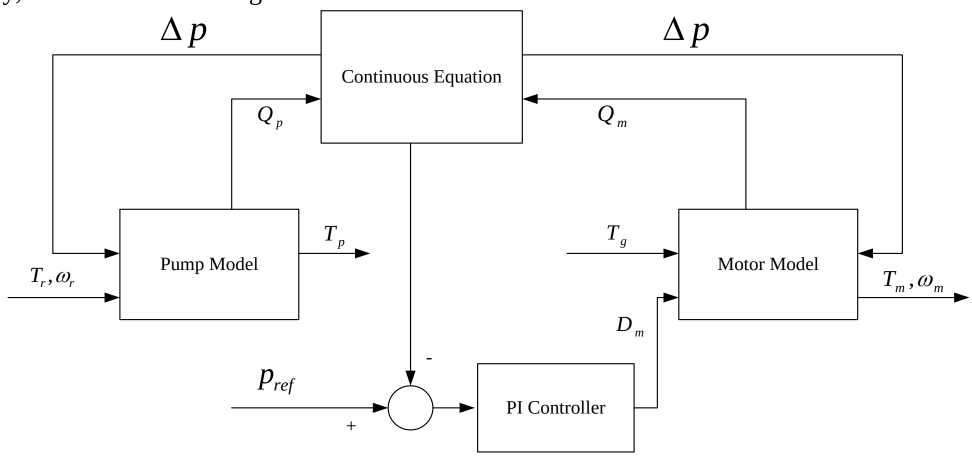

FIGURE 2. Control block diagram of hydrostatic transmission.

CONTROL LAW OF HYDROSTATIC SPEED CONTROL

In this section, we demonstrated several levels of control system. A supervisory controller with monitors is used to determine the time to start up and shut down for safety due to the wind speed data from anemometer. Second, the mechanical performance should be controlled under the constraints of wind turbine. Torque, control, which is driven by the electrical power generator, could extract a proper torque to generate an optimal power in different wind input. Meanwhile, the extracted torque, opposite to rotor mechanical torque driven by aerodynamics, achieves rotor speed control in some specific regions. The pitch control should be motivated to reduce the aerodynamic loading to protect the generator from over speed when the extracted wind power exceeds the rated power. Finally, the controls of generator including grid integration and power system will be set as the lowest level, which is also negligible in this study.

For the energy capture of view, Region 2 and Region 3 are more important than others. The objective of this variable speed control in Region 2 is to extract the energy as much as possible. This can be achieved by manipulating the rotor speed to reach the optimal point in current wind input. The optimal power curve is determined by the optimal tip-speed ratio which is the ratio between the tangential speed of the tip of a blade and the velocity of the wind, as shown in Eq.(8).

$$\lambda = \frac{R_b \omega_r}{v_w} \tag{8}$$

For specific control law in this region, a widely used strategy in wind industry, also referred to as the law $K\omega^2$ [12-13]. In this control, the control torque can be derived as follows:

$$\tau_p = K\omega_r^2 \tag{9}$$

where K refers to the control gain of the torque commend and ω_r is angular speed in rotor side. The control gain can be given by the combining Eq.(8)with Eq.(9):

$$K = \frac{\tau_p}{\omega_r^2} = \frac{P_w/\omega}{\omega_r^2} = \frac{1}{2}\rho A R_b^3 \frac{C_{p\max}}{\lambda_{opt}^3} \tag{10}$$

Thus, the control target has converted from variable speed control to variable torque control to maximize the energy that can be captured from the wind. Since the pump displacement is fixed, the optimal extracted torque should be achieved by varying the pressure difference Δp in HST circuit which infers to the control of motor displacement. Moreover, to achieve continuous variable speed control, field oriented control from doubly fed induction generator is used so that the speed can be control independently regardless the fluctuating wind input. Finally, a torque reference calculated by Eq.(9) was transformed to a pressure reference as a tracking commend:

$$\Delta p_{ref} = \frac{\tau_{ref} \cdot \eta_{mech,p}}{D_p \cdot 2\pi} \tag{11}$$

After wind speed reaches the rated wind speed (12m/s), the system will reach maximum rated power limited by induction generator. In this region, pitch actuator drives the blade to reduce the aerodynamic loads. However, the generator still extracts rated power (around 2MW) to keep the system maintaining the maximum power output. The error between the current rotor speed and the rated rotor speed feedbacks to a PI controller. The output of this PI-controller is used as reference pitch signal to the pitch system. The controller can be designed as:

$$u = (K_p + \frac{K_i}{s})e \tag{12}$$

SIMULATION RESULTS

The validity of user-built control strategy and the performance of real time response are shown in this section with the $K\omega^2$ control law and the MPPT(maximum power point tracking) control by implementing the specific wind input where the specifications are listed in Table 1. The referenced model of wind turbine was built by FAST, developed by NREL, 2006. As shown in figure 3, by combining with FAST, ADAMS, and MATLAB/SIMULINK, the aerodynamic, mechanism dynamic and control system dynamic simulation can be calculated simultaneously under different input of wind. Meanwhile, dynamic models of the main subsystems such as the pitch/yaw control systems and the direct driven permeant magnetic synchronized generator (PMSG) are developed in MATLAB/SIMULINK combined with the control strategies of overall wind turbine system to implement power tracking control.

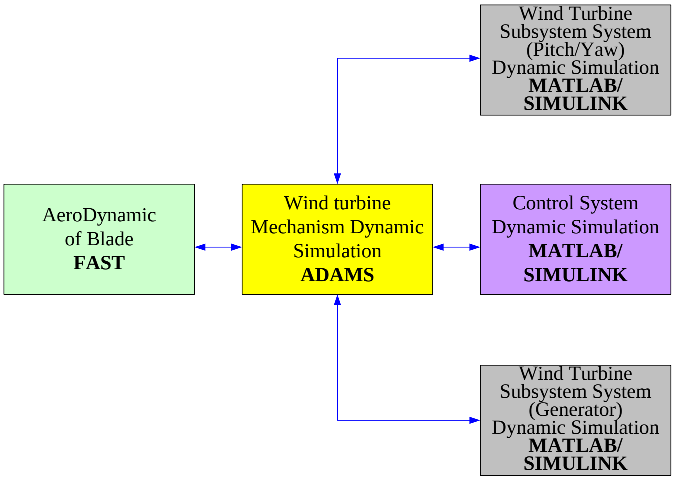

FIGURE 3. Co-simulation of FAST (Aerodynamics), ADAMS (Mechanism Dynamic) and MATLAB/ SIMULINK (subsystems and control system) for wind turbines.

Figure 4 illustrates the overall co-simulation system in MATLAB/SIMULINK where the orange block is the interface of MATLAB/SIMULINK and ADAMS. By referencing the current state variables such as power, pitch angle, and rotor speed, control regions are categorized and determined in region classification. Then the corresponding control operation and procedure are implemented afterward such that the optimal control references are chosen to capture the optimal power from the wind.

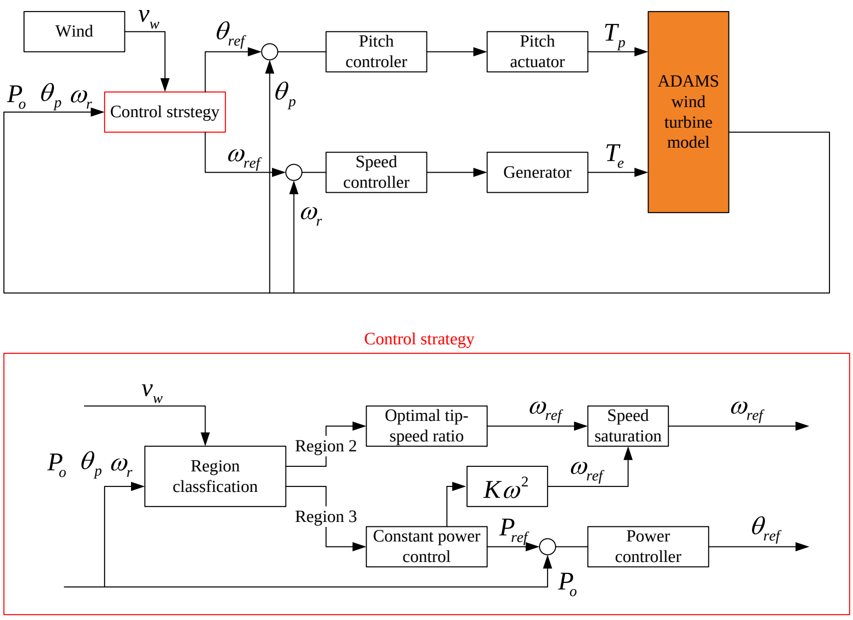

FIGURE 4. Overall co-simulation system in MATLAB/SIMULINK.

TABLE 1. Turbine specification.

Turbine components	Specification
Power level	2MW
Blade type	Three blades, horizontal
Pump size	4824 c.c./rev, fixed
Pump rated speed	26.9 rpm
Motor size	330 c.c./ rev, variable
Motor rated speed	1500 rpm

The purposes of hydrostatic transmission are to achieve variable continuous speed control and reduce power ripple from the wind. What's more, the hydraulic components can reduce the weight of nacelle when comparing with gearbox transmission. The input wind profile is designed as a turbulent wind input where its mean value is settled at rated wind speed. Referenced by IEC-61400-1, the wind turbine should be well performed under this wind load to fit the requirement. In the simulation result, a reference model of direct-drive wind turbine is used as a control group such that the influence on the wind turbine caught by the hydrostatic transmission can be observed in dynamic performance, and power ripple. Noted that the direct-drive wind turbine connected with permanent magnetic synchronous generator instead of doubly fed induction generator.

Figure 5 to Figure 7 are the results of subsystem response under normal turbulence model. Figure 5 shows the pitch response for the hydrostatic speed control wind turbine in overall closed-loop simulation for pitch response and errors for each blade. Figure 6 shows the tracking performance for the hydrostatic speed controlled wind turbine in closed-loop simulation for (a) pressure response, (b) pressure tracking error, (c) motor speed response, and (d) speed tracking error. Finally, the speed and power coefficient for the hydrostatic speed controlled wind turbine in closed-loop simulation for (a) output power (b) reactive power, (c) wind profile, and (d) power coefficient are shown in Figure 7. Before the rated power has been reached, the system followed the $K\omega^2$ law to extract the optimal torque from 0 to 20 secs, shown in figure11. The variable pitch control was activated after 20 secs to reduce the extra aerodynamic load. The advantages and drawbacks of HST can be recognized as follows: First, the power output in the transient region (20 secs) of Figure 7(a) is smaller than the direct-drive wind turbine. It can be attributed to the less efficiency of hydraulic components which also drive the pitch to a smaller attack angle to absorb more energies in Figure 5. However, the power can still be maintained at rated power when the wind exceeds the rated wind speed by adjusting the pitch angle. All the result showed that the pitch angle can still be adjusted by the power controller to change the aerodynamic loads so that the more efficient power extraction can be implemented. What's more, the power ripple in Figure 7 is alleviated by the characteristics of HST. Although, the efficiency in the low speed region is much less than the direct drive wind turbine, the hydrostatic transmission still shows the advantages of the power transmission and valid variable speed control in operation mode.

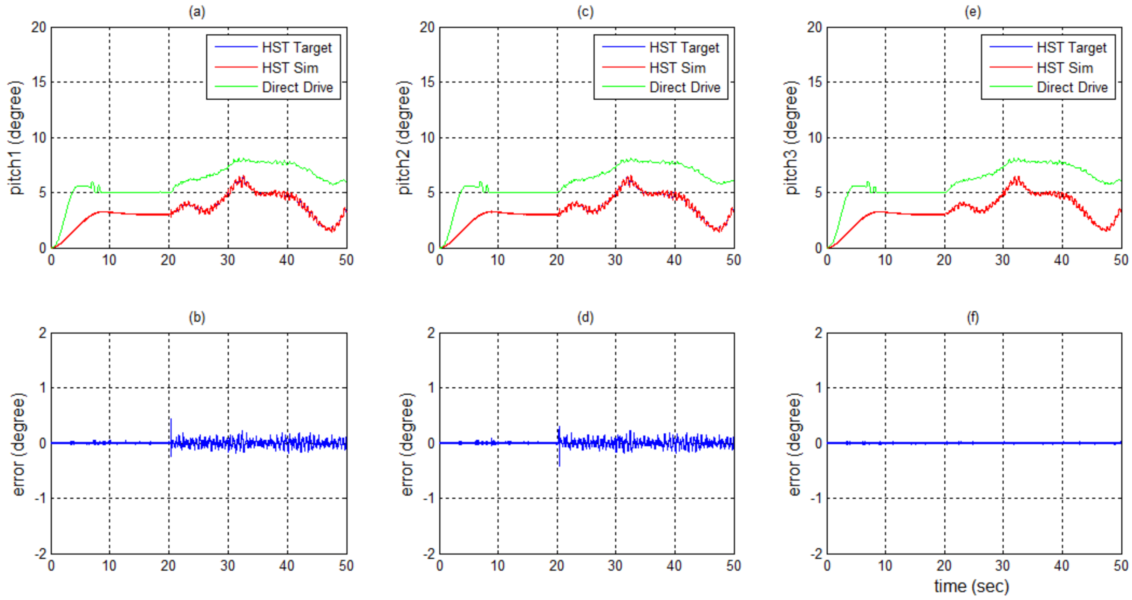

FIGURE 5. Pitch response for the hydrostatic speed controlled wind turbine in overall closed-loop simulation, NTM: (a) pitch 1 response (b) pitch 1 error (c) pitch 2 response (d) pitch 2 error (e) pitch 3 response (f) pitch 3 error.

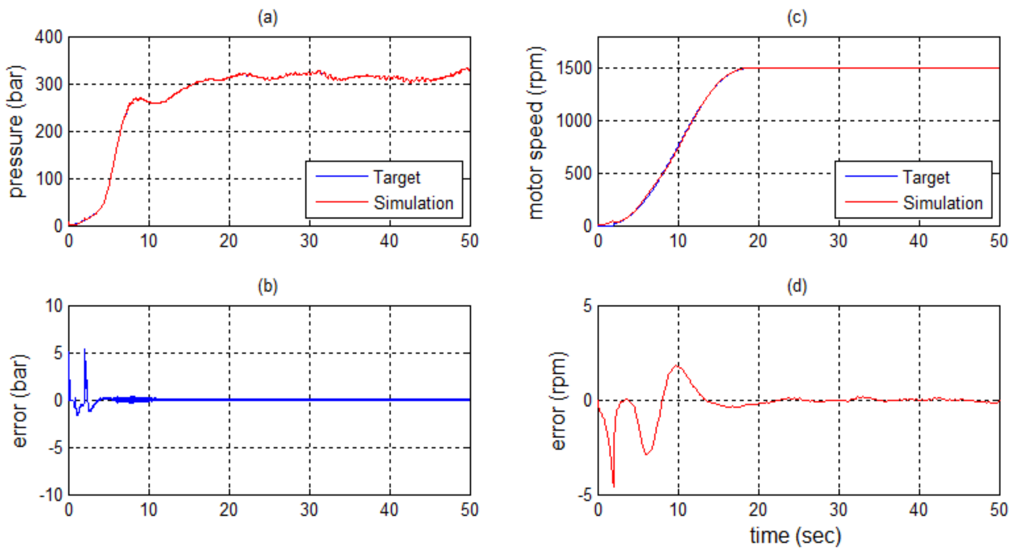

FIGURE 6. Tracking performance for the hydrostatic speed controlled wind turbine in closed-loop simulation, NTM: (a) pressure response (b) pressure tracking error (c) motor speed response (d) speed tracking error

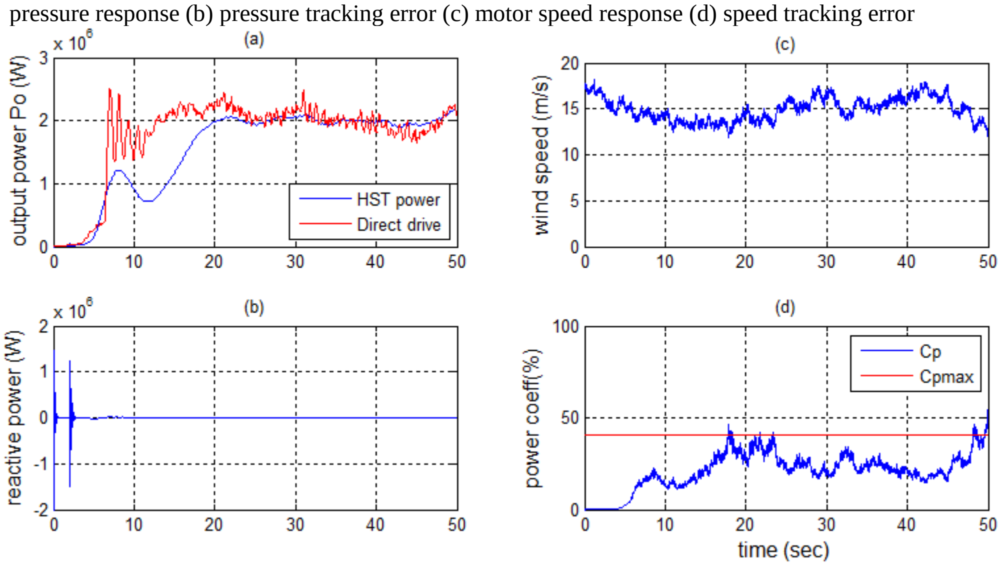

FIGURE 7. Power response of the hydrostatic speed controlled wind turbine in overall closed-loop simulation, NTM: (a) output power (b) reactive power (c) wind profile (d) power coefficient

CONCLUSION

This study not only proposed an idea of hydrostatic transmission model for offshore wind turbine but also applied it into wind turbine overall system closed-loop simulation. All of them were built up to drive the components simultaneously and testify the idea of hydrostatic transmission. Besides, a proper system controller with control strategies was set up to achieve the optimal power tracking control and the torque tracking control with $K\omega^2$ law. The wind turbine with hydrostatic transmission had 70% of efficiency comparing with the direct drive wind turbine but with more stable power extraction in generator side. Besides, the simulation results in different region proved the system controller worked perfectly in a correct mode with a good response based on the different subsystem design. However, there still exists some drawbacks of this simulation that can be improved in the future study. In order to reduce the computational difficulty, some assumptions were made to simplify the model. For instance, the volume flow efficiency of the pump and the orifice loss for each valve are assumed as a constant value instead of a pressure dependent variables. Besides, the scales of the pump and motor should be investigated with the current commercial product to ensure the validity of this hydrostatic transmission.

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REFERENCES

1. Y. Vidal, L. Acho, N. Luo, M. Zapateiro, and F. Pozo, "Power Control Design for Variable-Speed Wind Turbines," Energies, vol. 5, p. 3033, 2012.
2. X.-M. Guo, D. Sun, B.-T. He, and L.-L. Huang, "Direct power control for wind-turbine driven doubly-fed induction generator with constant switch frequency," in Electrical Machines and Systems, 2007. ICEMS. International Conference, pp. 253-258, 2007.
3. A. Tanvir, A. Merabet, and R. Beguenane, "Real-Time Control of Active and Reactive Power for Doubly Fed Induction Generator (DFIG)-Based Wind Energy Conversion System," Energies, vol. 8, p. 10389, 2015.
4. F. Deng and Z. Chen, "Low-voltage ride-through of variable speed wind turbines with permanent magnet synchronous generator," in Industrial Electronics, 2009. IECON '09. 35th Annual Conference of IEEE, pp. 621-626, 2009.
5. B. T. F. Wang, and K. A. Stelson, "Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production," presented at the The 8th International Conference on Fluid Power Transmission and Control, Hangzhou, China, 2013.
6. F. W. a. K. A. Stelson, "Model predictive control for a mid-sized hydrostatic wind turbine," presented at the the 13th Scandinavian International Conference on Fluid Power, Linköping, Sweden, 2013.
7. B. Thul, R. Dutta and K. A. Stelson, "Hydrostatic transmission for mid size wind turbines," presented at the Proceedings of the 52nd National Conference of Fluid Power, Las Vegas, 2011.
8. F. Wang, B. Trietch, and K. A. Stelson, "Mid-sized wind turbine with hydro-mechanical transmission demonstrates improved energy production," presented at the The 8th International Conference on Fluid Power Transmission and Control, Hangzhou, China, 2013.
9. Z. Jianzhong, C. Ming, and C. Zhe, "Design of wind turbine controller by using wind turbine codes," in Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on, pp. 2591-2595, 2008.
10. R. Fadaeinedjad, G. Moschopoulos, and M. Moallem, "Simulation of a Wind Turbine with Doubly-Fed Induction Machine Using FAST and Simulink," in Industrial Electronics, 2006 IEEE International Symposium on, pp. 2648-2653, 2006.
11. A. Anis, "Simulation of Slider Crank Mechanism Using ADAMS Software," International Journal of Engineering & Technology, vol. 12, pp. 108-112, 2012.
12. A. Merabet, J. Thongam, and J. Gu, "Torque and pitch angle control for variable speed wind turbines in all operating regimes," in Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on, pp. 1-5, 2011.
13. K. E. Johnson, L. J. Fingersh, M. J. Balas, and L. Y. Pao, "Methods for Increasing Region 2 Power Capture on a Variable-Speed Wind Turbine," Journal of Solar Energy Engineering, vol. 126, pp. 1092-1100, 2004.

